

# Production and Spectroscopy of Heavy Hadrons at the LHC

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Measurements of heavy flavor production and decay have featured prominently in the early results from the four large LHC experiments: ALICE, ATLAS, CMS, and LHCb. These results provide tests of QCD models in a new energy region and point the way toward future measurements of  $CP$  violation and searches for new physics. An overview of open heavy flavor studies is presented here, focusing on how the new measurements extend our knowledge of this area of physics. Heavy quarkonia states at the LHC are summarized in other proceedings of this conference. I also discuss briefly how heavy flavor measurements are likely to evolve as LHC luminosities increase.

## 1 Introduction

Heavy hadron production and spectroscopy are not primary focuses of any of the four large LHC experiments. Nevertheless, each of the collaborations have produced interesting and important results in this area. In fact, more than 50 heavy flavor results were available from ALICE, ATLAS, CMS, and LHCb at the time of this conference. Clearly, I will not be able to cover them all in this brief review. Rather, I'll attempt to concentrate on large themes in the field and discuss how recent results from the LHC have contributed to our understanding in these areas. Necessarily, I will be forced to gloss over many interesting details of the measurements I mention. More information on these measurements can be found in the numerous and excellent parallel talks by LHC speakers at Hadron2011. Results from the LHC in the related topics of charmonium [1] and bottomonium [2] can be found in two separate plenary talks. However, some important heavy flavor measurements will be skipped, not because of lack of interest, but simply because of lack of space. These include: measurements of many heavy flavor states that have been observed previously; studies of  $CP$ -violation and other electro-weak topics; the search for rare  $B$  and  $D$  decays; and all of top-quark physics.

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## 2 Experimental Issues

The wealth of results presented here was made possible, in large part, by the excellent performance of the LHC machine. Results discussed in these proceedings were obtained with up to  $40 \text{ pb}^{-1}$  data taken in 2010 where maximum peak luminosities of  $2 \times 10^{32} \text{ cm}^{-2} \cdot \text{s}^{-1}$  were observed. Already, at the time of this conference in June 2011, LHC peak luminosity had been increased by an order of magnitude and more than  $1 \text{ fb}^{-1}$  had been delivered to ATLAS and CMS. Approximately a third of that was seen by LHCb, which limits instantaneous luminosity to protect its delicate vertex detectors. As we will see, this rapidly increasing luminosity has important consequences for the heavy flavor production and spectroscopy programs at the four experiments, particularly ALICE, ATLAS, and CMS.

Another important factor in obtaining the results that I will discuss is the excellent performance of the detectors. All of them recorded collisions from the LHC with more than 90% efficiency in 2010. The detectors themselves are described in detail in references [3–6]. Their most important attributes for the study of heavy flavors are: angular acceptance, triggering, tracking, and particle identification. In order to understand the results produced by the experiments, it's useful to compare their approaches in each of these areas.

An extremely important feature of the experiments for heavy flavor related measurements is the range that they cover in  $\eta \equiv -\ln[\tan(\theta/2)]$ . Heavy quarks are produced predominantly in the forward region ( $|\eta| \gtrsim 1.5$ ) in proton-proton collisions at LHC energies. However backgrounds also peak in this area making the extraction of signals more difficult. ATLAS and CMS are “central” detectors, with muon coverage of  $|\eta| < 2.7$  and  $|\eta| < 2.4$ , respectively. ALICE also has central coverage for electrons,  $|\eta| < 0.9$ , but detects muons in the forward direction,  $-4.0 < \eta < -2.5$ . Finally, LHCb has only forward coverage:  $1.9 < \eta < 4.9$ . These acceptances are summarized in Fig. 1.

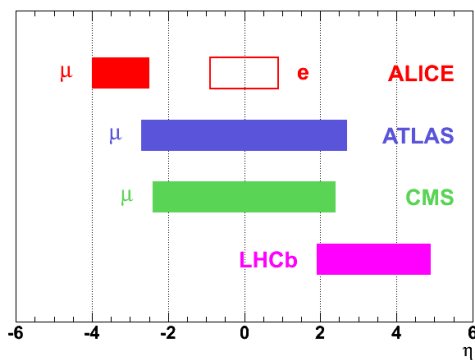
Of all the elements of the LHC detectors, trigger systems are perhaps the most critical in constraining the heavy flavor capabilities of the experiments. To deal with the challenge of selecting  $\sim 200 \text{ Hz}$  of interesting events from the  $40 \text{ MHz}$  rate of bunch crossings, the experiments have constructed complicated, multi-level trigger systems. Even with state-of-the-art triggers, though, heavy flavors present many difficulties. Heavy flavor events tend to have lower  $p_T$  scales than most electro-weak or new physics processes. Thus, their properties overlap much more strongly with the overwhelming background of light quark production than do, for example, those of  $W$ ,  $Z$ , or Higgs events. This problem is exacerbated as luminosities go up and the average number of proton-proton collisions per bunch crossing increases.

The experiments deal with these problems in a variety of ways. For those analyses that need inclusive event selections, “minimum-bias” or low  $p_T$  jet triggers must be used, but these gave acceptable rates only during very early LHC running when luminosities were orders of magnitude lower than present values. Hence, inclusive analyses tend to be constrained to only a tiny fraction of the total LHC running period. Since heavy hadrons

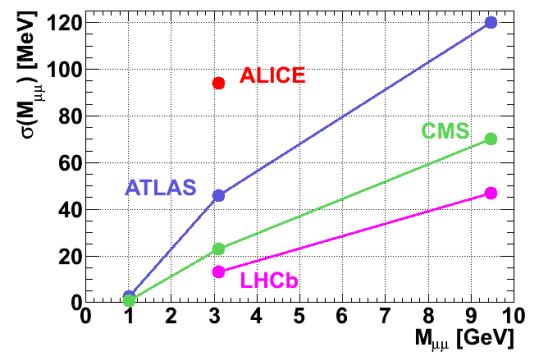
decay semi-leptonically with branching ratios of  $\mathcal{O}(10\%)$ , triggers that are sensitive to leptons (particularly muons) can be very effective at selecting events containing  $B$ - and  $D$ -hadrons – but only those decaying to muons. Additionally, trigger rates for the relatively low  $p_T$  muons ( $<10$  GeV) that tend to be produced in  $B$  and  $D$  decays quickly become untenable as luminosities increase. So the most effective single-muon triggers for heavy flavor physics were eliminated fairly early in the 2010 run. Only low  $p_T$  dimuon triggers remain active, and even those are seeing their thresholds gradually creep up. Finally, LHCb takes advantage of its unique capabilities to construct displaced vertex triggers at its lowest trigger level (the other experiments employ displaced vertex triggers at higher levels). These triggers remain unprescaled to the highest luminosity allowed by LHCb and give it access to fully hadronic decays of heavy hadrons.

Once events are accepted by the trigger system, offline reconstruction of their properties becomes the most important consideration. Tracking and particle identification are particularly critical for heavy hadrons. In the area of tracking two issues often arise in heavy flavor analyses: mass reconstruction and secondary vertex finding. The accuracy of the first of these depends primarily on precise measurements of track momenta, while the second is driven by the spatial (hit) resolution achievable by individual tracking elements and by the position of the inner-most tracking element. The vertexing performance of all four detectors is fairly similar. As an example, each achieves an impact parameter resolution of  $\sim 30$   $\mu\text{m}$  for tracks in the 5–10 GeV range. Larger differences are seen in mass resolution, as illustrated in Fig. 2, with LHCb having the clear advantage here.

Finally, particle identification is an important part of most heavy flavor analyses. All four of the experiments have excellent capabilities to identify leptons, and each has some handles on  $\pi/K/p$  separation. However, LHCb makes the most extensive use of hadron identification in the results presented here. Their RICH detectors allow them to tag  $\sim 95\%$  of charged kaons with a pion contamination of only 7%.



**Figure 1:** Angular acceptances of the four large LHC experiments.



**Figure 2:** Dimuon mass resolution vs invariant mass for the four large LHC experiments.

### 3 Heavy Flavor Production

The study of beauty and charm production at colliders has a long and interesting history. Because of the relatively high  $b$  and  $c$  quark masses, perturbative calculations of their production were expected to converge rather quickly. However, until the early 2000's, measurements of  $b$  production at the Tevatron and HERA were generally factors of 2–3 higher than Next to Leading Order (NLO) predictions. The shape of the  $b$ -production spectrum and charm production were much better described. For a more detailed review of the situation see reference [7]. This problem was largely resolved (see reference [8] for a review) by a combination of experimental and theoretical improvements. On the theoretical side, problems due to large  $\ln(p_T/m_b)$  terms at high  $b$ -quark  $p_T$  were ameliorated by the use of Fixed Order Next to Leading Log (FONLL) resummation; and consistent, FONLL, treatment of fragmentation functions in the calculations was achieved. Experimentally, collaborations made use of these consistent calculations, took more care in reporting observations that were less sensitive to fragmentation/hadronization uncertainties ( $B$ -hadron and  $b$ -jet cross-sections), and used updated values of Parton Density Functions and  $\alpha_s$ .

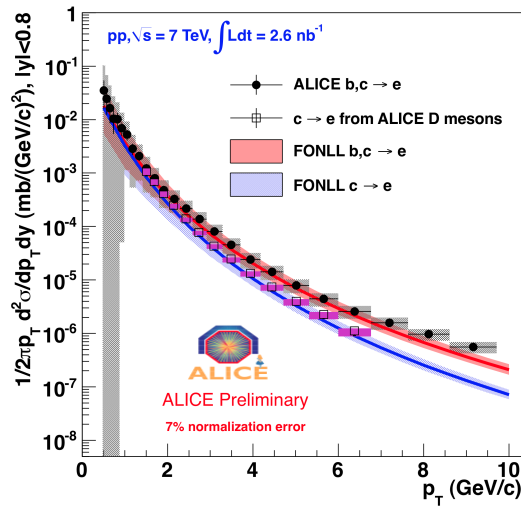
The result of these improvements was generally excellent agreement between measurement and NLO prediction [8]. However, it is important to verify that this agreement is maintained at the high energies of LHC collisions. At the present time, our NLO understanding has been incorporated into the standard, Leading Order (LO) event generators, PYTHIA [9] and HERWIG [10] through a variety of interfaces (MC@NLO [11], POWHEG [12], FONLL [13] are used in the analyses presented here) all implementing the calculations in slightly different ways. Additionally, intermediate implementations of beyond-LO calculations also exist (for example, MadGraph/MadEvent [15] and CASCADE [14]) that allow specific features of those calculations to be probed. All of these can be used to create detailed predictions that can be compared directly to experimental data.

#### 3.1 Inclusive Heavy Flavor Production

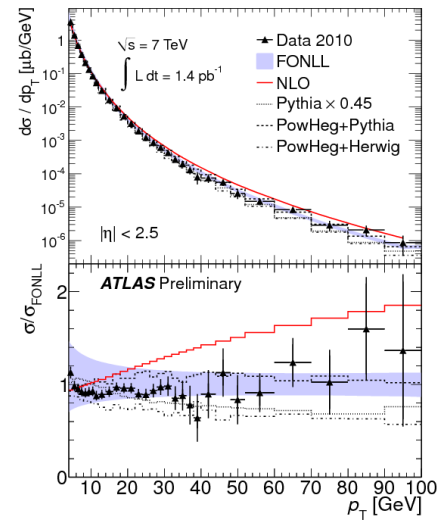
Preliminary, inclusive measurements of heavy flavor production in  $pp$  collisions at  $\sqrt{s} = 7$  TeV have been made by the ALICE and ATLAS collaborations. Inclusive samples of electrons and muons are selected by both experiments. ALICE considers electrons in the central region ( $|\eta| < 0.8$ ) in  $2.6 \text{ nb}^{-1}$  of data and subtracts a mix of “photonic” background from  $\gamma$  conversions,  $\pi^0$ , and other Dalitz decays based on the measured  $\pi^0$  cross-section. They measure muons in the forward region ( $-4 < \eta < -2.5$ ) using a  $16.5 \text{ pb}^{-1}$  data set. These samples are dominated by  $b$  and  $c$  decays to leptons. Both measurements agree quite well with FONLL predictions, as shown (for the electron case) in Fig. 3.

The ATLAS analysis [16] uses  $1.3\text{--}1.4 \text{ pb}^{-1}$  of data selected with single electron and muon triggers of varying thresholds. Theoretical predictions for Drell-Yan  $W/Z/\gamma^*$  are subtracted resulting in spectra that are dominated by heavy flavor decays. The collaboration reports

differential cross-sections for electrons in the kinematic range,  $7 < p_T < 26$  GeV and  $|\eta| < 2.0$ ; and for muons in the range,  $4 < p_T < 100$  GeV and  $|\eta| < 2.5$ . These measurements are compared to predictions using FONLL, POWHEG+PYTHIA, and POWHEG+HERWIG. Figure 4 shows the muon result. Good agreement is observed between both measurements and the FONLL prediction. The generators, POWHEG+PYTHIA and POWHEG+HERWIG, also do a reasonably good job although the HERWIG version predicts a significantly lower cross-section. Interestingly, the ATLAS muon data now has enough reach in  $p_T$  to be sensitive to the deviation between the pure NLO and the FONLL calculations that becomes significant for  $p_T > 35$  GeV. The data indicates clearly the need for an NLL resummation at high  $p_T$ .



**Figure 3:** The differential  $pp \rightarrow eX$  cross-section at  $\sqrt{s} = 7$  TeV measured by ALICE in  $|y| < 0.8$ .



**Figure 4:** The differential  $pp \rightarrow \mu X$  cross-section at  $\sqrt{s} = 7$  TeV measured by ATLAS in  $|\eta| < 2.5$ .

## 3.2 Charm Production

ALICE, ATLAS, and LHCb have all made preliminary measurements of charm production using samples of  $D$  mesons collected using micro- or minimum-bias triggers. The ALICE result is based on samples of  $D^0 \rightarrow K^- \pi^+$ ,  $D^+ \rightarrow K^- \pi^+ \pi^+$ , and  $D^{*+} \rightarrow D^0(K^- \pi^+) \pi^+$  (and charge conjugate) decays selected from  $1.6 \text{ nb}^{-1}$ , about 20% of the 2010 data. They measure differential cross-sections in the range  $2 < p_T < 12$  GeV in different rapidity ranges that are then adjusted to  $|y| < 0.5$ . ATLAS uses  $D^+ \rightarrow K^- \pi^+ \pi^+$ ,  $D^{*+} \rightarrow D^0(K^- \pi^+) \pi^+$ , and  $D_s^+ \rightarrow \phi(K^+ K^-)$  (and charge conjugate) decays in  $1.1 \text{ nb}^{-1}$  of data taken during early 2010 running to measure differential cross-sections in the kinematic range,  $p_T > 3.5$  GeV (extending to  $\sim 40$  GeV) and  $|\eta| < 2.1$  [17]. These data contain contributions from both  $c$ - and  $b$ -quark production. However, charm production dominates by approximately a factor

of 20. Finally, LHCb reconstructs all of the above decay modes using  $1.18 \text{ nb}^{-1}$  of early data taken with a micro-bias trigger in the kinematic region,  $0 < p_T < 8 \text{ GeV}$ . They present differential cross-sections in several rapidity region in  $2 < y < 4.5$  [18]. Charm and beauty components to this data sample are separated using a fit to the  $D$  meson impact parameter distribution.

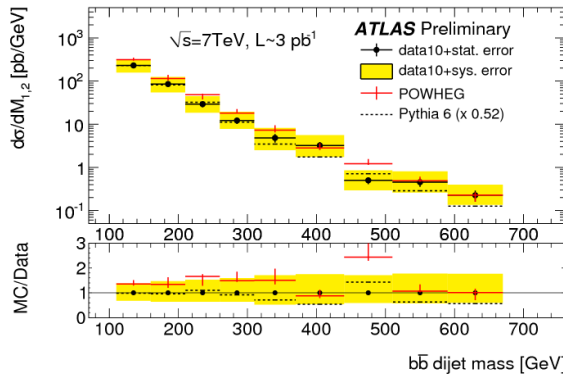
All differential cross-section results are in good agreement with NLO predictions in a variety of different implementations. However, uncertainties on these predictions are quite large and measurements are now limited by systematics.

### 3.3 Beauty Production

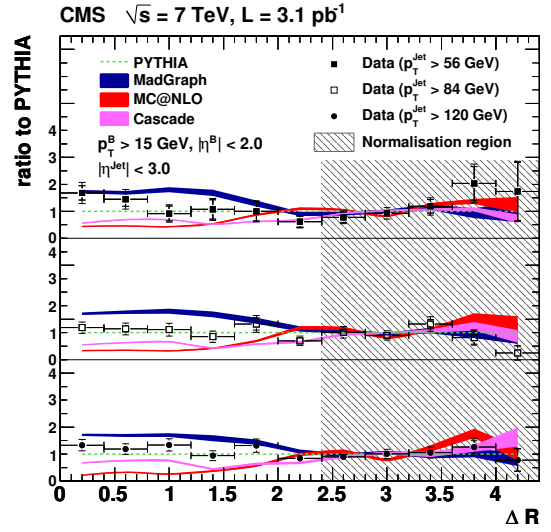
Beauty production at the LHC is measured using a wide variety of different methods. ATLAS [19] and CMS [20] separate  $b$ -production from lighter quark events using the momenta of muons transverse to a nearby jet's direction ( $p_T^{\text{rel}}$ ) as a discriminant that is sensitive to the underlying parton's mass. In samples of  $4.8 \text{ pb}^{-1}$  collected with low  $p_T$  muon+jet triggers (ATLAS), and  $85 \text{ nb}^{-1}$  of low  $p_T$  single-muon triggers (CMS) the collaborations measure differential cross-sections as a function of  $b$ -jet  $p_T$  (ATLAS) and muon  $p_T$  (CMS). Another inclusive method employed by ATLAS [21] and CMS [22] selects  $b$ -quark events using jets containing reconstructed secondary vertices in  $3.0 \text{ pb}^{-1}$  and  $60 \text{ nb}^{-1}$ , respectively, of data taken using a mixture of minimum-bias and jet triggers. This method allows sensitivity to higher values of jet  $p_T$  (up to  $260 \text{ GeV}$ ) than the  $p_T^{\text{rel}}$  technique. The substantial  $B$ -hadron lifetime also provides a handle on  $B$ -hadron production in several partially inclusive results. LHCb uses the  $D^0$  impact parameter distribution of  $pp \rightarrow \mu D^0 X$  candidates in  $2.9 \text{ nb}^{-1}$  of micro-bias, and  $12.1 \text{ nb}^{-1}$  of single-muon trigger data to measure the  $pp \rightarrow H_b X$  cross-section in several bins between  $2 < \eta < 6$  [23]. ATLAS [24], CMS [25], and LHCb [26] all use a pseudo-proper time variable in their  $J/\psi$  analyses to measure the  $b \rightarrow J/\psi X$  differential cross-section as well. Finally, CMS has made  $B$ -hadron differential cross-section measurements using the exclusive decay modes  $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$  [27],  $B_d \rightarrow J/\psi(\mu^+\mu^-)K_S^0$  [28], and  $B_s \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$  [29] (and conjugates) collected using their dimuon triggers. These measurements all agree quite well with a variety of NLO calculations, with the possible exception the exclusive mode cross-sections where the NLO predictions are consistently lower than the measurements. But again the uncertainties on the experimental results are generally dominated by systematic effects even with the small amounts of integrated luminosity used.

To probe the calculations more deeply, correlations between the produced  $b$  and  $\bar{b}$  need to be used. First results in this area are now available from ATLAS and CMS. ATLAS uses its secondary vertexing analysis [21] to select events with two identified  $b$ -jets. The dijet invariant mass that they observe is shown in Fig. 5. Agreement with POWHEG+PYTHIA predictions is good across a wide range of dijet masses. CMS, on the other hand, probes correlations between the  $b$  and  $\bar{b}$  using angular variables. Their analysis [30], which uses  $3.1 \text{ nb}^{-1}$  of single-jet trigger data, searches for events with two reconstructed secondary vertices

from which they reconstruct the opening angle between the two  $B$ -hadrons responsible for the vertices. This technique allows access to the events with very small  $B\bar{B}$  opening angles that are particularly sensitive to NLO effects. An example of their results is shown in Fig. 6, where the angular separation,  $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ , between the  $B\bar{B}$  pair observed in CMS data and predicted by various beyond LO calculations is plotted compared to the LO PYTHIA prediction. None of the higher order predictions do a good job describing the data in the low  $\Delta R$  region where higher order effects are expected to dominate.



**Figure 5:** The differential  $pp \rightarrow b\bar{b}$  cross-section as a function of  $b\bar{b}$  dijet invariant mass measured for  $b$ -jets with  $p_T > 40$  GeV and  $|y| < 2.1$  at ATLAS.



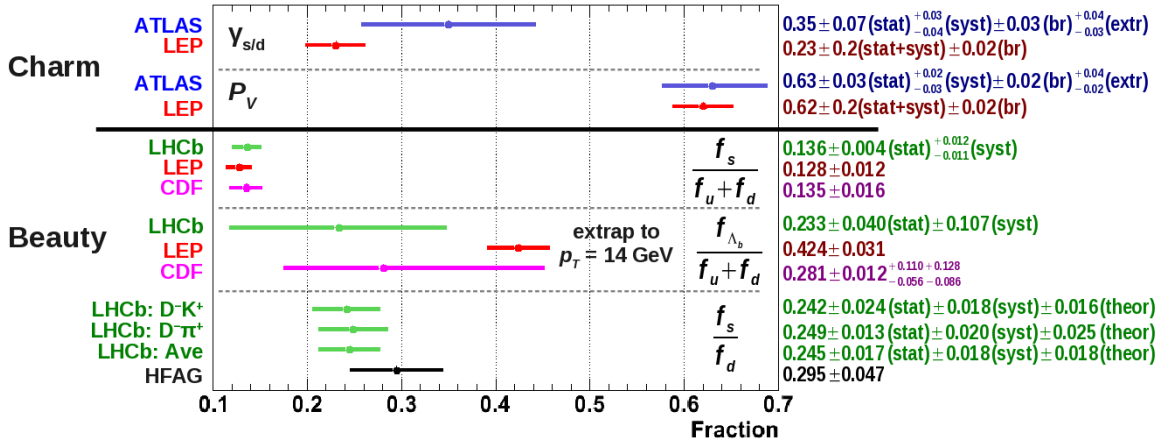
**Figure 6:** Ratios of differential  $B\bar{B}$  cross-sections as a function of  $\Delta R$  measured by CMS compared to various predictions.

### 3.4 Heavy Flavor Fragmentation

Another important component in our understanding of heavy flavor production is the process of fragmentation of  $b$ - and  $c$ -quarks into beauty and charm hadrons of various flavors. The ATLAS and LHCb collaborations have produced new measurements in these areas. The ATLAS study of  $D^{(*)}$  meson production [17] allows the measurement of several charm fragmentation related parameters after subtracting predicted  $B$ -hadron decay contributions from their measured  $D^{(*)}$  meson cross-sections and extrapolating these  $c\bar{c}$  measurements to the full kinematic phase space. ATLAS derives a strangeness suppression factor,  $\gamma_{s/d}$ , which corresponds to the ratio of the total  $D_s^\pm$  production cross section from  $c\bar{c}$ ,  $\sigma_{c\bar{c}}^{tot}(D_s^\pm)$ , to the sum of  $\sigma_{c\bar{c}}^{tot}(D^{*\pm})$  and the part of  $\sigma_{c\bar{c}}^{tot}(D^\pm)$  that does not arise from  $D^{*\pm}$  decays. ATLAS also measures the fraction of  $D$  mesons produced in the vector state,  $P_V$ , as the ratio of  $D^{*\pm}$  to the sum of  $D^{*\pm}$  and  $D^\pm$  production. Both measurements are in good agreement with averages of LEP results [17, 31] as shown in Fig. 7.

LHCb fragmentation measurements concentrate on the  $b$ -quark sector. They have determined the ratio of  $b$ -quarks fragmenting to hadrons containing  $s$ - and  $d$ -quarks,  $f_s/f_d$ , using  $B^0 \rightarrow D^- \pi^+$ ,  $B^0 \rightarrow D^- K^+$  and  $B_s \rightarrow D_s^- \pi^+$  decays in  $35 \text{ nb}^{-1}$  of data [32]. They have also determined the strange quark fraction,  $f_s/(f_u + f_d)$  and the  $\Lambda_b$  baryon fraction,  $f_{\Lambda_b}/(f_u + f_d)$  in  $b$ -quark fragmentation using  $3 \text{ pb}^{-1}$  samples of semi-muonic decays of  $B$ -hadrons [33]. They observe no dependence of the strange quark fraction on  $p_T$  or  $\eta$ , but do see evidence of a linear dependence of the  $\Lambda_b$  fraction on  $p_T$  in all  $\eta$  regions they consider. As can be seen in Fig. 7, their results are consistent with <sup>2</sup>, but more precise than, the current world averages [34] and individual results from CDF [35] and LEP [34].

Finally, LHCb has observed a clear signal of  $43 \pm 13$  events, in  $32.5 \text{ pb}^{-1}$  of data, for the decay  $B_c^+ \rightarrow J/\psi \pi^+$  [36]. Comparing this to the production of  $B^\pm \rightarrow J/\psi K^\pm$  yields a ratio,  $\sigma(B_c^+) \times B(B_c^+ \rightarrow J/\psi \pi^+) / \sigma(B^+) \times B(B^+ \rightarrow J/\psi K^+) = (2.2 \pm 0.8 \pm 0.2)\%$ , in good agreement with a prediction made using the BcVegPy generator [37],  $(1.4 \pm 0.4 \pm 0.1)\%$ .



**Figure 7:** A summary of beauty and charm hadron fragmentation fraction measurements. Note: to allow a consistent comparison, the  $f_{\Lambda_b}$  results are extrapolated to  $p_T = 14 \text{ GeV}$  using LHCb's parametrization [33].

## 4 Spectroscopy and Exclusive Final States

All heavy flavor hadrons are produced copiously at the LHC and each of the large experiments have reconstructed sizable samples of most of the low-lying states. However, exclusive reconstruction of beauty and charm hadrons is an area where LHCb is taking a leading role. Their ability to trigger on hadronic decays and their efficient  $\pi/K/p$  identification capabilities, as well as other detector optimizations, make exclusive final state reconstruction one of their strengths.

<sup>2</sup>In the case of the  $\Lambda_b$  fraction, all results have been adjusted to an average  $p_T$  of  $14 \text{ GeV}$ .



LHCb takes advantage of this strength in several ways. In the areas of hadron properties, they have been able to identify several new hadronic decays of  $B_s$  mesons with the data they have taken to date. They are also using exclusively reconstructed decays as a tool to study electro-weak symmetry breaking and to search for new physics through measurements of parameters of the CKM matrix. Of particular interest here are measurements of the angles  $\gamma \equiv \arg(-V_{ub}^* V_{ud} / v_{cb}^* V_{cd})$  and  $\beta_s \equiv \arg(-V_{tb}^* V_{ts} / v_{cb}^* V_{cs})$ , which are currently the most poorly measured of the “unitarity triangle” quantities.

LHCb has observed several new decay modes of the  $B_s$  meson. They have studied  $B_s$  decays to excited  $c\bar{s}$  states:  $B_s \rightarrow \mu D_{s1} X$  and  $B_s \rightarrow \mu D_{s2}^* X$  with  $D_{s1}^+, D_{s2}^{*+} \rightarrow D^0(K^- \pi^+) K^+$  [38]. Measurements of the relative fractions of these states allow sensitive tests of QCD models. Using data samples of 20 and 3  $\text{pb}^{-1}$ , LHCb finds  $\mathcal{B}(\overline{B}_s^0 \rightarrow D_{s2}^{*+} X \mu^- \bar{\nu}) / \mathcal{B}(\overline{B}_s^0 \rightarrow X \mu^- \bar{\nu}) = (3.3 \pm 1.0 \pm 0.4)\%$  and  $\mathcal{B}(\overline{B}_s^0 \rightarrow D_{s1}^+ X \mu^- \bar{\nu}) / \mathcal{B}(\overline{B}_s^0 \rightarrow X \mu^- \bar{\nu}) = (5.4 \pm 1.2 \pm 0.4)\%$ . The  $D_{s1}$  result is in good agreement with a previous measurement by the D0 collaboration [39], but this is the first observation of the  $D_{s2}^*$  decay mode. These measurements are in general agreement with predictions of 3.2% and 5.7% respectively from the ISGW2 model [40] but slightly higher than quark model expectations of 1.8% and 2% [41].

LHCb has also made a first observation of the decay mode  $B_s^0 \rightarrow K^{*0} \overline{K}^{*0}$ , which proceeds solely through loop  $b \rightarrow s$  diagrams in the Standard Model, and can be used in the extraction of  $\gamma$  and  $\beta_s$ . Using 35  $\text{fb}^{-1}$  of data they observe a signal with  $7\sigma$  significance, as shown in Fig. 8, and measure  $\mathcal{B}(B_s^0 \rightarrow K^{*0} \overline{K}^{*0}) = [1.95 \pm 0.47(\text{stat}) \pm 0.51(\text{syst}) \pm 0.29(f_d/f_s)] \times 10^{-5}$  [42] in reasonable agreement with the prediction of  $(0.79_{-0.39}^{+0.43}) \times 10^{-5}$  based on QCD factorization [43].

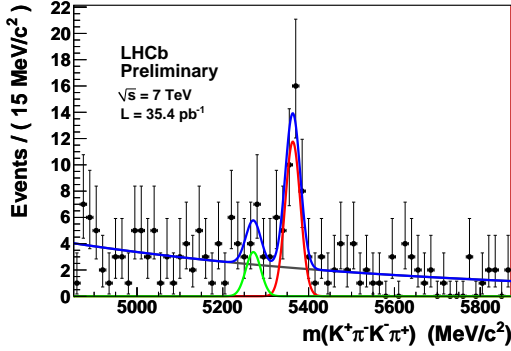
Measurement of the angle  $\gamma$  to date have relied primarily on  $B^- \rightarrow D^{(*)} K^{(*)-}$  decays. However, many other modes also have the potential to contribute. These include  $B^0 \rightarrow D^0 K^{*0}$ ,  $B^- \rightarrow D^0 K^- \pi^+ \pi^-$ ,  $\overline{B}^0 \rightarrow D^+ \pi^- \pi^+ \pi^-$ , and  $B_s^0 \rightarrow D_s^+ K^- \pi^+ \pi^-$ . LHCb has taken first steps toward widening the scope of  $\gamma$  measurements by observing several of these decays or closely related final states. They measure

| Mode  | Events         | Branching Ratio ( $\times 10^4$ )   | Ref. |
|---|----------------|---|------|
| $\overline{B}_s^0 \rightarrow D^0 K^{(*)0}$             | $34.5 \pm 6.9$ | $4.44 \pm 1.00(\text{stat}) \pm 0.55(\text{syst})$<br>$\pm 0.56(f_s/f_d) \pm 0.69(B \rightarrow D\rho)$ | [44] |
| $\overline{B}^0 \rightarrow D^+ \pi^- \pi^+ \pi^-$      | $1151 \pm 45$  | $61.6 \pm 2.6 \pm 6.9$  | [45] |
| $B^- \rightarrow D^0 \pi^- \pi^+ \pi^-$                 | $973 \pm 45$   | $59.6 \pm 2.9 \pm 6.1$  | [45] |
| $\overline{B}_s^0 \rightarrow D_s^+ \pi^- \pi^+ \pi^-$  | $139 \pm 24$   | $62.8 \pm 11.0 \pm 12.1$  | [45] |
| $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ | $165 \pm 18$   | $122 \pm 14 \pm 46$   | [45] |

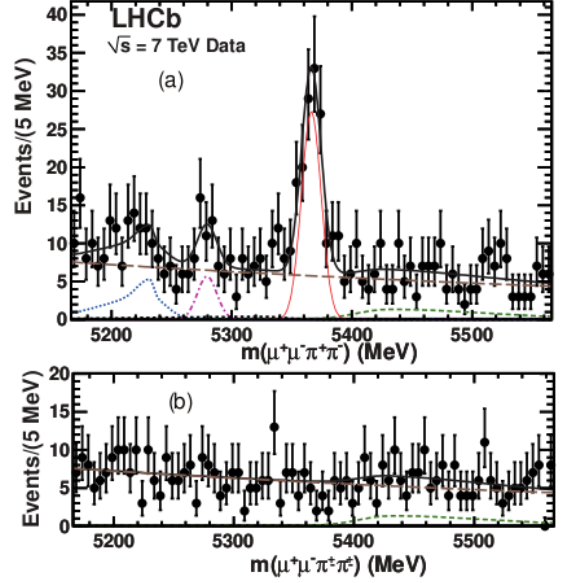
which represent either first observations of these final states (the first and last measurements listed above) or significant improvements over current world averages.

Finally, LHCb was the first to observe the decay  $B_s \rightarrow J/\psi[\mu^+ \mu^-] f_0(980)[\pi^+ \pi^-]$  [46]. As shown in Fig. 9 they see a clear peak in the  $J/\psi \pi^+ \pi^-$  distribution at the  $B_s$  mass in 33  $\text{pb}^{-1}$

of data. They measure  $\Gamma[B_s^0 \rightarrow J/\psi f_0(\pi^+\pi^-)]/\Gamma[B_s^0 \rightarrow J/\psi \phi(K^+K^-)] = 0.252^{+0.046+0.027}_{-0.032-0.033}$  in good agreement with the later D0 measurement of  $0.210 \pm 0.032 \pm 0.036$  [47]. This decay is similar to  $B_s \rightarrow J/\psi \phi$ , which is commonly used to determine the angle  $\beta_s$ . However, since the  $J/\psi f_0$  mode consists of a single  $CP$ -odd eigenstate, it can be used to extract  $\beta_s$  without having to rely on the complicated angular analysis necessary to disentangle the  $CP$  states in the  $J/\psi \phi$  mode.



**Figure 8:** The  $K^+\pi^-K^-\pi^+$  invariant mass distribution measured by LHCb in their  $B_s \rightarrow K^{*0}\bar{K}^{*0}$  analysis [42]



**Figure 9:** The  $J/\psi\pi^+\pi^-$  invariant mass distribution measured by LHCb in their  $B_s \rightarrow J/\psi f_0$  analysis [46] for right sign (top) and wrong sign  $\pi\pi$  combinations, where the  $\pi\pi$  mass is required to lie within 90 MeV of the  $f_0(980)$  mass.

## 5 Conclusions

The first year of LHC running has produced a wealth of results in the heavy flavor sector from ALICE, ATLAS, CMS, and LHCb. Each of the experiments has made measurements of open beauty and charm production. In general, the good agreement between data and NLO QCD predictions that was observed at the Tevatron continues to hold at higher LHC energies although most measurements are already systematics limited. Upon considering those measurements that are particularly sensitive to the details of the calculations, though, some areas of disagreement seem to be appearing. These are most evident in exclusive  $b$  production and in the angular correlations observed between  $b$  and  $\bar{b}$  jets. Unfortunately (for

these measurements), the rapidly increasing LHC luminosity requires all the experiments to move away from the inclusive, low  $p_T$  triggers that have provided the bulk of the data for production studies. In the future, these studies will need to shift focus, primarily to rely on those final states that are accessible using dimuon triggers (for example,  $\Lambda_b \rightarrow J/\psi \Lambda$ ). Even for these, muon  $p_T$  thresholds will steadily increase. Clearly, the next round of heavy flavor measurements will have to use different techniques than those described here.

Trigger considerations also affect the areas of exclusive final states and spectroscopy for ATLAS and CMS. However, the LHCb collaboration is truly starting to hit its stride here. They have already made several first observations of heavy flavor decay modes and are now beginning to have enough data to probe  $CP$  violation using a wide variety of techniques.

The next few years will be challenging ones for the heavy flavor efforts of the four large LHC experiments. Overcoming the difficulties posed by increasing luminosity and the demands of ever higher precision will require both perseverance and cleverness. The excellent results presented here, though, show that ALICE, ATLAS, CMS, and LHCb are up to the task. Look forward to even more interesting heavy flavor results from the LHC at the next meeting of this conference!

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## References

- [1] Y. Gao, these proceedings.
- [2] N. Leonardo, these proceedings.
- [3] K. Aamodt *et al.* [ALICE Collaboration], JINST **3**, S08002 (2008).
- [4] G. Aad *et al.* [ATLAS Collaboration], JINST **3**, S08003 (2008).
- [5] R. Adolphi *et al.* [CMS Collaboration], JINST **3**, S08004 (2008).
- [6] A. A. Alves *et al.* [LHCb Collaboration], JINST **3**, S08005 (2008).
- [7] M. Cacciari, arXiv:hep-ph/0407187.
- [8] M. Mangano, arXiv:hep-ph/0411020.
- [9] T. Sjostrand, S. Mrenna, P. Z. Skands, JHEP **05**, 026 (2006), arXiv:hep-ph/0603175.

- [10] G. Corcella *et al.*, JHEP **01**, 010 (2001), arXiv:hep-ph/0011363.
- [11] S. Frixione, B. R. Webber, JHEP **06**, 029 (2002), arXiv:hep-ph/0204244.  
S. Frixione, P. Nason, B. R. Webber, JHEP **08**, 007 (2003), arXiv:hep-ph/0305252.
- [12] P. Nason, JHEP **11**, 040 (2004), arXiv:hep-ph/0409146.  
S. Frixione, P. Nason, G. Ridolfi, JHEP **09**, 126 (2007), arXiv:0707.3088[hep-ph].  
S. Frixione, P. Nason, C. Oleari, JHEP **11**, 070 (2007), arXiv:0709.2092[hep-ph].  
S. Alioli, P. Nason, C. Oleari, E. Re, JHEP **06**, 043 (2010), arXiv:1002.2581[hep-ph].
- [13] M. Cacciari, P. Nason, C. Oleari, JHEP **04**, 006 (2006), arXiv:hep-ph/0510032.
- [14] H. Jung, G. P. Salam, Eur. Phys. J. **C19**, 351 (2001), arXiv:hep-ph/0012143.
- [15] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, JHEP **06**, 128 (2011), arXiv:1106.0522[hep-ph].
- [16] G. Aad *et al.* [ATLAS Collaboration], arXiv:1109.0525[hep-ex].
- [17] The ATLAS Collaboration, ATLAS-CONF-2011-017.
- [18] The LHCb Collaboration, LHCb-CONF-2010-013.
- [19] The ATLAS Collaboration, ATLAS-CONF-2011-057
- [20] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1103**, 090 (2011), arXiv:1101.3512[hep-ex].
- [21] The ATLAS Collaboration, ATLAS-CONF-2011-056.
- [22] The CMS Collaboration, CMS-PAS-BPH-10-009.
- [23] R. Aaij *et al.* [LHCb Collaboration], Phys. Lett. **B694**, 209 (2010), arXiv:1009.2731[hep-ex].
- [24] G. Aad *et al.* [ATLAS Collaboration], Nucl. Phys. **B850**, 387 (2011), arXiv:1104.3038[hep-ex].
- [25] V. Khachatryan *et al.* [CMS Collaboration], Eur. Phys. J. **C71**, 1575 (2011), arXiv:1011.4193[hep-ex].
- [26] R. Aaij *et al.* [LHCb Collaboration], Eur. Phys. J. **C71**, 1645 (2011), arXiv:1103.0423[hep-ex].
- [27] V. Khachatryan *et al.* [CMS Collaboration], Phys. Rev. Lett. **106**, 112001 (2011), arXiv:1101.0131[hep-ex].

- [28] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **106**, 252001 (2011), arXiv:1104.2892 [hep-ex].
- [29] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. **D84**, 052008 (2011), arXiv:1106.4048 [hep-ex].
- [30] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1103**, 136 (2011), arXiv:1102.3194 [hep-ex].
- [31] L. Gladilin, arXiv:hep-ex/9912064.
- [32] The LHCb Collaboration, LHCb-CONF-2011-013.
- [33] The LHCb Collaboration, LHCb-CONF-2011-028.
- [34] D. Asner *et al.* [Heavy Flavor Averaging Group], arXiv:1010.1589 [hep-ex].
- [35] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. **D77**, 072003 (2008), arXiv:0801.4375 [hep-ex].
- [36] The LHCb Collaboration, LHCb-CONF-2011-017.
- [37] C. -H. Chang, C. Driouichi, P. Eerola, X. G. Wu, Comp. Phys. Commun. **159**, 192 (2004), arXiv:hep-ph/0309120. C. -H. Chang, J. -X. Wang, X. -G. Wu, Comp. Phys. Commun. **175**, 624 (2006), arXiv:hep-ph/0604238.
- [38] R. Aaij *et al.* [LHCb Collaboration], Phys. Lett. **B698**, 14 (2011), arXiv:1102.0348 [hep-ex].
- [39] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **102**, 051801 (2009), arXiv:0712.3789 [hep-ex].
- [40] D. Scora, N. Isgur, Phys. Rev. **D52**, 2783 (1995), arXiv:hep-ph/9503486.
- [41] H. B. Mayorga, A. Moreno Briceno, J. H. Munoz, J. Phys. **G29**, 2059 (2003), arXiv:hep-ph/0209032.
- [42] The LHCb Collaboration, LHCb-CONF-2011-019.
- [43] M. Beneke, J. Rohrer, D. Yang, Nucl. Phys. **B774**, 64 (2007), arXiv:hep-ph/0612290.
- [44] The LHCb Collaboration, LHCb-CONF-2011-008.
- [45] The LHCb Collaboration, LHCb-CONF-2011-007.
- [46] R. Aaij *et al.* [LHCb Collaboration], Phys. Lett. **B698**, 115 (2011), arXiv:1102.0206 [hep-ex].
- [47] The D0 Collaboration, D0 Note 6152 (2011).